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Non-fossil-resources-based Hydrogen Production Technology
— Key to Sustainable Hydrogen Energy Systems —

RYOTA OMORI
Environment and Energy Unit

8.1 Introduction

In the face of global energy and environmental concerns, there is a growing need to simultaneously deal with the issues represented by "3E," namely, energy supply, environmental conservation, and economic growth.

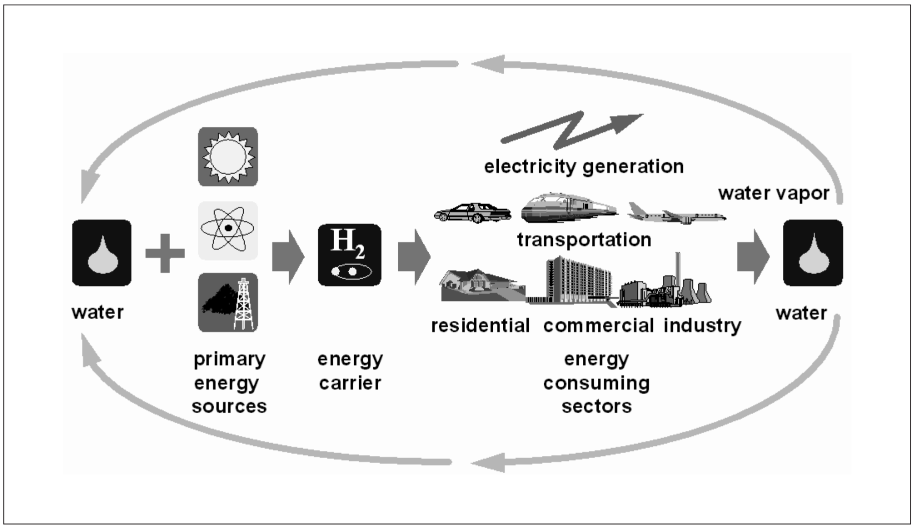
With this situation as a backdrop, hydrogen-energy-based systems such as fuel cells are receiving widespread attention. Hydrogen along with electricity is expected to play a major role as a source of secondary energy in the future.

In promoting hydrogen energy, however, it is indispensable that a variety of element technologies are developed and the infrastructure improved with respect to fuel cells and the production, transportation, storage and utilization of hydrogen. While global competition in this particular area heats up, both industry and academia in Japan have been pouring significant resources into research and development of fuel cells and hydrogen energy systems, the achievements of which are being published in succession through scientific journals and mass media.

The government is also active in developing promotional strategies and budgetary measures. The Council for Science and Technology Policy (CSTP), for instance, set the "2003 Guidelines for the Distribution of Budgets and Human Resources in Science and Technology" [1] in June, specifying fuel cells and the use of hydrogen as "priority areas and issues to be promoted" in the energy field.

Likewise, the Strategic Research Council on the Commercialization of Fuel Cell Technology under the Ministry of Economy, Trade and Industry specified five advantages in introducing fuel cells - i.e., energy saving, reductions in the environmental burden, diversified energy supply and substitution of oil, merits associated with decentralized power sources, and improved industrial competitiveness and development of new industries. The council positioned fuel cells as a key technology in the fields of energy and the environment in the 21st century.[2]

Figure 1: Two phenomena occurring on the surface of titanium oxide photocatalyst



Fuel cells are, so to speak, power generators using hydrogen as fuel; they generate electricity through the chemical reaction between hydrogen and oxygen, which produces water. Fuel cells, themselves, discharge water only. Hydrogen gas, however, does not exist naturally in any significant quantity on Earth, and hence it should be produced from fossil resources, biomass, water, etc.

At the moment, the widely held view is that hydrogen production will be heavily dependent on natural gas and other fossil resources. Underlying this view are scores of problems associated with the non-fossil-resources-based hydrogen production technology, the commercialization and spread of which are likely to take considerable time.

However, in view of conserving fossil resources and reducing greenhouse gas emissions, transition to the non-fossil-resources-based hydrogen production technology is required in the long run. Widespread applications of technology for producing hydrogen from resources such as water and biomass through the use of renewable and nuclear energy will dramatically conserve fossil resources and reduce greenhouse gas emissions (Section 8.3.3 addresses a quantitative study on these issues). Expectations for the commercialization of such sustainable hydrogen energy systems constitute the backbone of today's research on fuel cells and hydrogen energy. Figure 1 shows the hydrogen energy cycle using hydrogen derived from water.

Prospects for when and how these sorts of "ideal system" will be commercialized have a substantial influence on the significance and contents of policies for the introduction, commercialization and R&D strategies concerning fuel cells and hydrogen energy in the future. Determining the potential of the non-fossil-resources-based hydrogen production technology is thus critical for Japan in developing not only long-term but also short-to-medium term energy policies and R&D strategies.

For these reasons, this article will focus on the non-fossil-resources-based hydrogen production technology. Specifically, Chapter 8.2 provides an introduction to hydrogen energy and fuel cells; Chapter 8.3 reviews in a quantitative manner its significance in solving the 3E problem, based on the achievements of previous studies; Chapter 8.4 outlines trends in the research and development of mainstay technologies; and Chapter 8.5 rounds up findings and provides suggestions.

8.2 Hydrogen energy and fuel cells

Hydrogen along with electricity is expected to play a major role as a source of secondary energy in the energy system of the 21st century. Electricity can be converted into hydrogen, and vice versa; they are complementary to each other as follows:[4]

- Hydrogen can be stored in bulk, which is not the case with electricity;
- Electricity can transmit energy without moving substances, which is not the case with hydrogen;
- Hydrogen can be used as chemical fuel and industrial materials, which is not the case with electricity;
- Electricity can be used for processing and storing information, which is not the case with hydrogen; and
- Hydrogen is suitable for long-distance transportation, while electricity is an ideal medium for short-distance transportation.

Fuel cells are the most promising system for making use of hydrogen energy. The principle of fuel cells is the opposite of water electrolysis; they produce electricity through the chemical reaction between hydrogen and oxygen, which produces water. As shown in Table 1, fuel cells can be categorized into four types in terms of the electrolytes they use — i.e., the solid oxide type (SOFC), the molten carbonate type (MCFC), the phosphoric acid type (PAFC), and the polymer electrolyte type (PEFC). Fuel cells are used primarily for fuel cell vehicles (FCV), stationary power sources for domestic and business use (including cogeneration systems) and power sources for portable equipment.

Table 2 shows the "prospective targets for introduction" specified in the Strategic Research Council Report on the Commercialization of Fuel

Table 1: Four types of fuel cells [5], [6]

	Solid Oxide Type (SOFC)	Molten Carbonate Type (MCFC)	Phosphoric Acid Type (PAFC)	Polymer Electrolyte Type (PEFC)
Electrolyte	Stabilized zirconia	Carbonate	Phosphate	Ion exchange membrane
Fuel (Reactant)	Hydrogen, carbon monoxide	Hydrogen, carbon monoxide	Hydrogen	Hydrogen
Operational Temp.	900-1,000℃	650-700℃	200℃	70-90℃
Power Generation Efficiency (HHV)	45-55%	45-50%	40-45%	35-40%
Characteristics	High power generation efficiency Accommodates internal reforming	High power generation efficiency Accommodates internal reforming	Soon to be commercialized Difficult to start and stop operations	Can be operated at low temperatures High energy density Relatively easy to start and stop operations
Development Status	Demonstration stage	Demonstration stage	Commercialization stage	Soon to be put into practical use
Applications	Centralized large-scale power generation, decentralized power sources, cogeneration systems	Centralized large-scale power generation, decentralized power sources, cogeneration systems	Decentralized power sources, cogeneration systems	Vehicles, domestic cogeneration systems, portable power sources

Table 2: Prospective targets for the introduction of fuel cells commercialization conference (cumulative amount) [3]

Period	Description of the Period	Targets for Introduction by the End of the Period	
		Fuel Cell Vehicles	Stationary Fuel Cell
2002 - 2004	Period for improving infrastructure and demonstrating technology	-	-
2005 - 2010	Period for introduction	50,000 units	2.1 million kW
2010 - 2020	Period for applications	5 million units	10 million kW

Cell Technology (for the polymer electrolyte fuel cells).[2]

8.3 The significance of the non-fossil-resources-based hydrogen production technology — from the viewpoint of solving the “3E” problem

As mentioned earlier, molecular hydrogen does not exist naturally in any significant quantity on Earth, and, hence, hydrogen for fuel cells should be produced on- or off-site. In the case of fuel cell vehicles, hydrogen can be produced off-site and transported for use for fuel cell vehicles (pure hydrogen fuel cell vehicles), or it can be produced from methanol or gasoline by in-vehicle reformers (reformer fuel cell vehicles) (see Footnote 1). The advantage in introducing fuel cells (e.g., substitution of oil, energy saving and reductions in the environmental burden) depends largely on fuel types and their production methods.

This chapter outlines supply and demand trends of hydrogen and its production methods, provides the results of existing analyses regarding the effects of saving energy and reducing greenhouse gas emissions by fuel and production method, and sheds light on the significance of the non-fossil-

Footnote 1:

Fuel cells based on molten carbonates or solid oxides accommodate internal reforming, and can use natural gas and coal gas as fuel. However, their applications for vehicles and small-scale stationary power sources have yet to be examined.

resources-based hydrogen production technology.

8.3.1 Supply and demand trends of hydrogen

The world's hydrogen production currently stands at some 500 billion Nm^3 a year (Nm^3: volume at 0°C and 1 atm), most of which is produced by steam reforming of fossil fuel such as natural gas; about 40% of which is consumed by ammonium synthesis, and some 20% by oil refining. The world's largest steam-reforming plant can produce 100,000Nm^3 of hydrogen per hour.[7]

Domestic demand for hydrogen is estimated at 15-20 billion Nm^3 a year, about half of which is consumed by oil refining. As for applications for energy, 3-5 million Nm^3 of liquid hydrogen is used annually for launching space rockets.[5] On the other hand, more than 10 billion Nm^3 of hydrogen is produced annually as the by-product of steel-making, oil refining and ethylene production, most of which is consumed by the producers themselves as energy sources or materials for chemicals (a mere one percent, more or less, is sold on the market).

As shown in Table 2, the Strategic Research Council on the Commercialization of Fuel Cell Technology set the target for introducing fuel cell vehicles at 5 million units by 2020 (cumulative amount). About 5 million fuel cell vehicles on the road require some 14 billion m^3 of hydrogen per year.[8] If fuel cell vehicles become widespread in the future, commanding a 50% share of the total number of passenger vehicles (which currently stands at 53 million units[9]), five times this volume will be required to meet the expected demand. Taking into account hydrogen to be consumed by stationary fuel cells, much more hydrogen will be needed.

The widespread use of hydrogen energy systems will inevitably boost demand for hydrogen. How to produce hydrogen is thus a major challenge to be addressed, which in turn determines the entire framework of the systems.

8.3.2 Hydrogen production methods

Table 3 shows typical methods for producing hydrogen, which are broadly categorized into those using fossil resources and those using non-fossil resources, as materials or energy sources. The methods using fossil resources have been industrialized, but they emit large amounts of CO_2 (see Footnote 2). Take the steam-reforming process for instance: this mainstay method for producing hydrogen emits 0.9kg of CO_2 in producing 1m^3 of hydrogen even when using natural gas — a material that involves the least amount of CO_2 emissions.[7]

The methods using non-fossil resources can be categorized into; (1) water electrolysis using electricity derived from non-fossil fuel, (2) thermochemical water splitting, (3) biomass

Table 3: Hydrogen production methods

	Method	Material	Energy	Status of Technological Development
Fossil-resources-based	Steam reforming	Natural Gas, LPG, Naphtha	Heat	Commercialization
	Partial oxidation	LPG, Naphtha, Crude Oil, Coal	Heat	Commercialization
	Catalytic reforming	LPG, Naphtha	Heat	Commercialization
	Coke furnace gas	Coal	Heat	Commercialization
	Electrolysis	Water	Electricity (derived from fossil resources)	Commercialization
Non-fossil-resources-based	Electrolysis	Water	Electricity (derived from non-fossil resources)	Commercialization
	Thermochemical splitting	Water	Nuclear, Solar Heat	Demonstration stage
	Biomass conversion	Biomass	Heat, Bacteria, etc.	Demonstration stage
	Photolysis	Water	Sunlight	Basic study stage

Footnote 2:

Even when reforming fossil resources, zero emissions can be achieved at large-scale hydrogen production facilities through the applications of CO_2 recovery and sequestration technologies. There has been a growing interest in CO_2 underground storage; for details, refer to "Trends in the Development of Measures Against Global Warming Centered on CO_2 Underground Storage" (Kazuaki Miyamoto, the Jan. 2003 issue of Science & Technology Trends – Quarterly Review).

conversion, and (4) water photolysis, all of which virtually eliminate CO_2 emissions and the consumption of fossil resources. Of these, however, only the method based on "(1) water electrolysis" has been established so far.

8.3.3 Life cycle assessment of fuel-cell-based systems

Section 8.3.1 demonstrated that hydrogen production should be expanded dramatically in response to the widespread applications of hydrogen energy systems. Even if fossil resources are used for hydrogen production in this scenario, fossil resources can still be conserved and global warming gas emissions can be reduced on the condition that the energy efficiencies of fuel-cell-based systems (vehicles, stationary power sources, etc.) are higher than those of their conventional counterparts. Then, to what extent are they effective in these respects?

To answer this question, there is a need to assess the life cycle of fuel-cell-based systems — i.e., energy required for the extraction of raw materials, transportation, fuel production and the actual fuel consumption. This kind of assessment with respect to vehicles is called a "well-to-wheel" analysis.

Take CO_2 emissions for instance: in the case of conventional gasoline-powered vehicles, a large part of their lifecycle CO_2 emissions is attributable to their operations, while the extraction of crude oil and the production/transportation of gasoline involve less CO_2 emissions. By contrast, fuel cell vehicles loaded with hydrogen derived from fossil resources emit no CO_2 when they are being driven, while hydrogen production itself is a major source of their lifecycle CO_2 emissions.

Referring to the results of the life cycle assessment conducted by Thomas et al.,[11] and Wang,[12] the third IPCC report[10] addresses the effects of fuel cell vehicles in conserving energy and reducing greenhouse gas emissions. The New Energy and Industrial Technology Development Organization (NEDO) of Japan conducted a similar analysis through the project for developing hydrogen energy use technology (WE-NET) (see Footnote 3).[13] Based on these findings, this Chapter examines the effects of fuel cell systems in conserving fossil resources and reducing greenhouse gas emissions.

With regard to the effects of conserving fossil resources, the fuel economy figures of pure-

Figure 2: Assessment of the life cycle of greenhouse gas emissions [12]

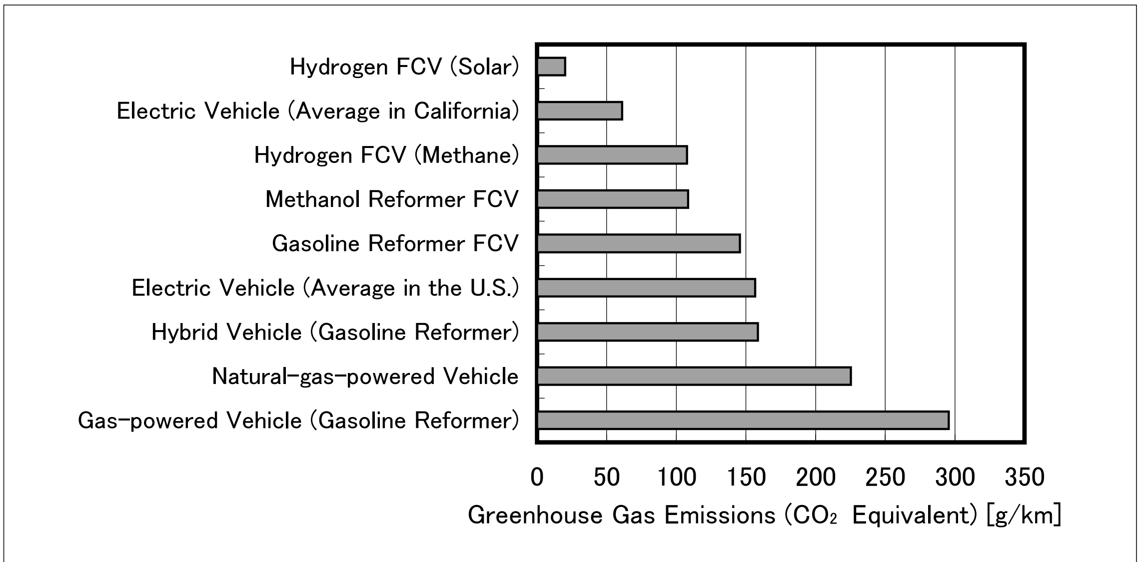
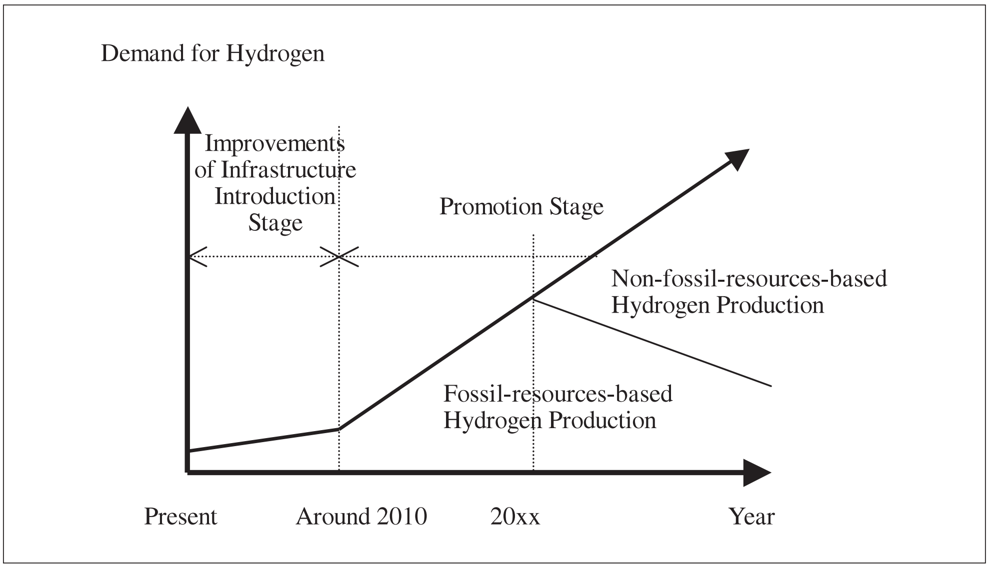


Figure 3: Transition to Non-fossil-resources-based hydrogen production technology



hydrogen fuel cell vehicles and methanol reformer fuel cell vehicles (see Footnote 4) improve by 75-250% and 25-125%, respectively, compared with those of conventional gasoline-powered vehicles, according to Thomas et al. Likewise, Wang's results show 180-215% and 110-150% improvements in fuel consumption, respectively. WE-NET concludes that the fuel consumption of gasoline reformer fuel cell vehicles is about three times lower than those of conventional gasoline-powered vehicles. Moreover, 40-60% improvement in energy consumption can be expected in using by-product hydrogen from coke furnaces, and for fuel cell vehicles using liquid fuel derived from natural gas. It is also noted here that gasoline hybrid vehicles and electric vehicles are likewise effective in conserving energy.

On the other hand, the total energy consumption of fuel cell vehicles using hydrogen derived from non-fossil resources depends largely on the energy sources to be used for hydrogen production, the place of its production and the transportation methods. Meanwhile, there have been discussions as to whether renewable energy should be included when calculating energy consumption. Whatever the case may be, the consumption of fossil resources will be reduced dramatically.

Figure 2 shows part of the results of Wang's life cycle assessment regarding the effects in reducing greenhouse gas emissions in the case of passenger vehicles in the U.S. In general, the amount of greenhouse gas emissions shows a trend similar to that of the results of fuel consumption. The amount of greenhouse gases emitted by gasoline or methanol reformer fuel cell vehicles and fuel cell vehicles using hydrogen derived from natural gas is lower than that emitted by conventional gasoline-powered vehicles by 50% and 60%, respectively. Likewise, electric vehicles reduce emissions by 50%, though depending on the makeup of power sources. Gasoline hybrid vehicles are similarly effective. Emissions can be reduced dramatically in the case of producing

Footnote 3:

The project was launched in fiscal 1993 with an eye toward the global use of renewable energy derived from hydrogen. Phase 1 of the R&D program (a six-year program, budgeted at ¥10 billion) of the project was completed in fiscal 1998, and Phase 2 of the R&D program was subsequently launched in fiscal 1999. Phase 2 will be completed in fiscal 2002, a year ahead of schedule, which will be consolidated into the "project for developing basic technology for the safe use of hydrogen" to be launched in fiscal 2003.

Footnote 4:

Fuel consumption, in this chapter, refers to the total amount of energy consumed by the whole process ranging from the extraction of materials to the driving of vehicles.

hydrogen from solar energy.

Up to this point, we have considered the assessment of fuel cell vehicles. According to the assessment conducted by WE-NET for decentralized stationary fuel cell power sources,[13] their energy efficiency and the amount of CO_2 emissions are almost the same as those of existing large-scale power generation systems, while lagging behind those of highly efficient LNG combined cycle power generation systems, as far as the "power generation" part is concerned. The performance of fuel cells as a cogeneration system is similar to or lower than that of cogeneration systems directly using city gas or light oil.

To sum up, even when using fossil resources to produce hydrogen, fuel cell vehicles are quite effective in conserving fossil resources and reducing greenhouse gas emissions. Fuel cell vehicles, however, compete directly with gasoline or natural gas powered hybrid vehicles and electric vehicles, and so do stationary fuel cells with cogeneration systems directly using city gas or light oil. Fuel-cell-based systems do not necessarily outperform these competing technologies.

Meanwhile, fossil-resources consumption and CO_2 emissions can be virtually eliminated if hydrogen is produced from such resources as water and biomass through the use of renewable or nuclear energy. From the viewpoint of solving the "3E" problem, therefore, it is preferable that the non-fossil-resources-based hydrogen production technology becomes widespread in the near future. Figure 3 shows a scenario for the transition to the non-fossil-resources-based hydrogen production technology.

8.4 Trends in the R&D of the non-fossil-resources-based hydrogen production technology

This chapter addresses hydrogen production methods that use no fossil resources as materials and energy sources, and divides these methods into four categories — (1) water electrolysis, (2) thermochemical water splitting, (3) biomass conversion, and (4) water photolysis - for outlining trends in the R&D of each method.

8.4.1 Water electrolysis

Water electrolysis is the simplest method for producing hydrogen. However, it involves a large amount of CO_2 emissions in the case of using electricity generated by such facilities as thermal power plants burning fossil resources. On the other hand, fossil-resources consumption and CO_2 emissions can be virtually eliminated if water is electrolyzed by the electricity derived from nuclear or renewable energy (including hydropower).

Since electricity is a valuable form of energy, there is a need to consider a balance with other electrical needs and minimize the total cost of energy supply when using electricity for large-scale hydrogen production. Primarily, this hydrogen production method should be promoted in relation to the utilization of nighttime electricity for improving plant availabilities and to output-leveling measures for connecting wind-power plants to the grid.

The electrolytic process of water can be broadly categorized into electrolysis using alkaline water and that using polymer electrolyte. The alkaline

Figure 4: Principle of water electrolysis based on the polymer electrolyte method [5]

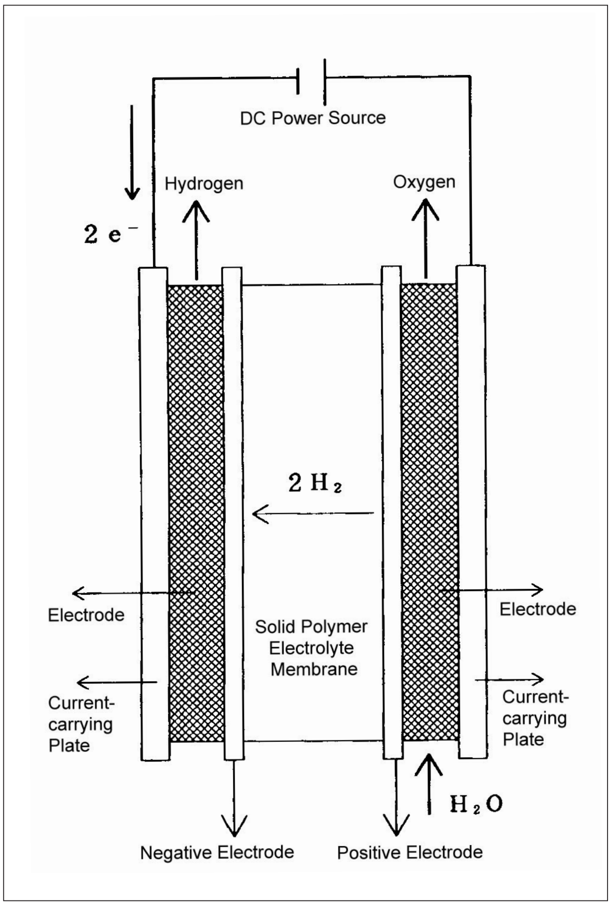


Figure 5: Hydrogen supply station (on-site hydrogen production type) based on the water electrolysis method [14]

water electrolysis method is already in commercial use; it is a simple method but low in energy conversion efficiency and susceptible to corrosion. Figure 4 shows the principle of the polymer electrolyte method:[5] a polymer electrolyte membrane (made of fluoropolymers) is sandwiched by platinum catalytic electrodes, porous electrodes and current-carrying plates. The porous electrodes function as a medium that conveys both electricity and gas/liquid — water is supplied to the positive electrode and hydrogen is generated by the negative electrode. This particular method, which has yet to be commercialized, is high in energy conversion efficiency, free from corrosion because of the absence of alkaline solution, and contributes to making equipment compact.

WE-NET has been conducting a project since 1993 for the technological development of water electrolysis based on the polymer electrolyte method. As part of this project, a hydrogen supply station (on-site hydrogen production type) was set up in February 2002 in the precinct of Shikoku Research Institute in Takamatsu. The station is one-tenth the size of commercial facilities and can produce 30Nm^3 of hydrogen per hour (see Figure 5).

8.4.2. Thermochemical water splitting

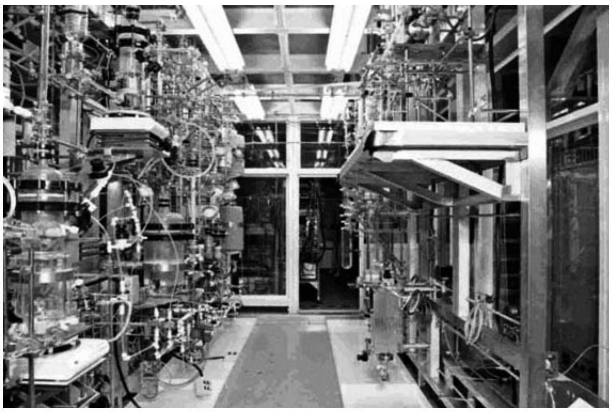
In theory, direct splitting of water requires a large amount of heat with temperatures exceeding 2,500ºC. A number of thermochemical processes have been proposed, each of which incorporates thermochemical reactions to split water at temperatures lower than 1,000ºC. In relation to this, nuclear energy and solar energy are considered their possible heat sources that emit no CO_2. In particular, the use of nuclear reactors is receiving attention as promising heat sources that can accommodate large-scale hydrogen production.[15]

Of the variety of thermochemical water splitting cycles, the "IS Process" is the most promising technique, which is being studied by the group led by the Japan Atomic Energy Research Institute.[16] This particular process, originally invented by General Atomics (U.S.), is designed to recycle iodine (which reacts with material water) and compounds derived from sulfur within the process in order to eliminate the release of hazardous substances. It involves the following three chemical reactions:

At the moment, high temperature gas reactors (HTGRs) are assumed to be the prospective heat sources for the IS Process. High temperature gas reactors can provide a large amount of heat with temperatures exceeding 900ºC and are relatively safe in the first place. Light water reactors, meanwhile, cannot accommodate the process because of their limited capacity for heat supply (300ºC or below).

The Japan Atomic Energy Research Institute developed continuous hydrogen production equipment (capacity: 50 liters per hour) in 2001 based on the IS Process, and subsequently launched relevant research programs. The equipment will be connected to a high-temperature engineering test reactor (HTTR) that

Figure 6: Continuous hydrogen production equipment based on the thermochemical water splitting method (IS process) (The Japan Atomic Energy Research Institute) [16]



(Left front: equipment for the Bunsen reaction process; left back: equipment for the sulfuric-acid decomposition process; and right back: equipment for the distillation of hydrogen iodide.)

Bunsen Reaction	$2H_2O + xI_2 + SO_2 = 2HIx + H_2SO_4$	Ambient Temp. to 100ºC
Decomposition of Hydrogen Iodide	$2HI = H_2 + I_2$	400ºC
+ Decomposition of Sulfuric Acid	$H_2SO_4 = H_2O + SO_2 + 1/2O_2$	800ºC
	$H_2O = H_2 + 1/2O_2$	

is being tested by the Institute. Figure 6 shows the external view of the equipment.

A one-million-kWe high temperature gas reactor that operates 7,000 hours a year can produce 3.4 billion Nm^3 of hydrogen per year (the heat efficiency of hydrogen production = 50%). A light water reactor with the same capacity can produce 1.7 billion Nm^3 of hydrogen per year through water electrolysis.[4] The thermochemical method, which needs no conversion of heat into electricity, outperforms the electrolysis method in total energy efficiency. Incidentally, it is estimated that the combination of a high temperature gas reactor and the IS Process produces hydrogen at a cost 1.5 times higher than that of the commercial steam reforming method using fossil resources.

Because of their large energy output with high density, nuclear power plants can accommodate large-scale hydrogen production; they are expected to be an option that can meet the expanding demand for hydrogen in the future, respond to environmental constraints and conserve fossil resources. However, thermochemical cycles that can make use of the heat generated by today's dominant light water reactors have yet to be developed.

8.4.3. Biomass conversion

Biomass refers to organic resources of plant origin such as agricultural waste, forestry waste, fishery waste, garbage and energy crops. Energy derived from these resources is called bioenergy, which is inexhaustible in its nature and thus receiving attention as a promising option for curbing global warming since, as a whole, it emits no CO_2. Hydrogen production processes using bioenergy, such as combustion heat, electricity, liquid fuel, etc., or biomass as materials generate CO_2, but the amount is equal to that produced by the original plants in the course of their growth. In a total sense, therefore, the use of biomass does not increase the CO_2 concentration in the atmosphere (carbon neutral).

Biomass takes a variety of forms, and so does hydrogen production using biomass. With the use of dry biomass, hydrogen can be produced primarily through the thermochemical gasification process. In this case, the combustion heat of biomass itself is generally used for increasing reaction temperatures. However, there is a need to reform or eliminate by-products such as carbon monoxide and hydrocarbon gases.

With respect to wet biomass, the methane fermentation process is already operational; hydrogen can be produced from methane, but the whole process takes several weeks. Other processes such as catalytic aqueous-phase reforming,[17] supercritical water gasification[18] and bacteria-based hydrogen fermentation[19] have been invented.

One of the advantages of biomass is that it can be readily converted into liquid fuel (ethanol, methanol, biodiesel, etc.). Methanol and hydrogen derived from biomass can be used for fuel cell vehicles, or they can be used directly as internal combustion fuel (see Footnote 5).

8.4.4. Water photolysis

Water photolysis is the technology where hydrogen is produced by splitting water through the use of solar light energy. This chapter addresses the direct photolysis of water using photocatalysts and the like — the area in which Japan has been taking the lead ever since the "Honda-Fujishima Effect",[20] water photolysis by an electrochemical cell made up of a titanium-dioxide electrode and a platinum electrode, was reported in 1972.

Scores of photocatalytic materials responding to

Footnote 5:

Comparison between these options goes beyond the scope of this article. In some states in Brazil and the U.S., ethanol produced from sugarcane and corn or a mixture of ethanol and gasoline are becoming popular as automotive fuel.

ultraviolet rays have been discovered so far, but the energy of these rays represents a mere 4% of solar light energy. In order to produce hydrogen efficiently, therefore, there is a need to develop photocatalysts that respond to a broad range of visible light (wavelength: 400-700nm), the energy of which represents some 43% of solar light energy.

Such photocatalysts with satisfactory stability and function have been considered difficult to develop. However, as some new findings have been reported recently, research in this particular area is gaining momentum.

The group led by Hironori Arakawa, director of the Photoreaction Control Research Center under the National Institute of Advanced Industrial Science and Technology, came up with a breakthrough: using a metal-oxide semiconductor ($In_{1-X}Ni_XTaO_4$, X=0-0.2), doping indium/tantalum oxides with nickel, for the first time in the world the group succeeded in fully photolyzing water (hydrogen:oxygen = 2:1) through the single-step photoexcitation of visible light, the results of which were published in Nature last year.[21] By doping nickel, the activity of photocatalysts for short-wavelength visible light improves dramatically, while it disappears for visible light with a wavelength longer than 550nm. The quantum efficiency stands at 0.66% for light with a wavelength of 402nm (see Footnote 6). The group also succeeded in fully photolyzing water with the use of visible light, imitating a two-step photoexcitation reaction, namely the photosynthesis mechanisms of plants.[22]

Even though under UV irradiation, Associate Professor Akihiko Kudo at the Science University of Tokyo succeeded in fully photolyzing water using $NiO/NaTaO_3$ doped with lanthanum, and produced hydrogen from a reaction tube (with a capacity of about 400ml) at a high rate of 20mmol/h (500ml/h).[23] Compared to water electrolysis, this performance corresponds to an electrolytic current of 1A or more, with its quantum efficiency reaching 50% at a wavelength of 270nm. As for photocatalysts responding to visible light, $SrTiO_3$ doped with Cr^{3+} and Ta^{5+} or Sb^{5+}, $NaInS_2$ and $AgInZn_7S_9$ are reported to exhibit high activity in hydrogen production, though under the existence of sacrificial agents (see Footnote 7).[24]

The group led by Professor Kazunari Domen at the Tokyo Institute of Technology is conducting another research in this area: aiming at developing photocatalysts capable of splitting water, the group focused on oxynitride/oxisulfide-based photocatalytic materials, and has been testing their response to visible light. The results show that $LaTiO_2N$, Ta_3N_5, TaON and $Sm_2Ti_2S_2O_5$ sufficiently absorb visible light with a wavelength up to 600nm.[25, 26]

The research on photocatalysts responding to visible light is becoming active not only for producing hydrogen but also for developing antifoulants, disinfectants and deodorants for building exteriors, car interiors, etc. This particular area is attractive to researchers in terms of the basic study relevant to materials science and catalyst science.

As far as hydrogen production is concerned, however, water photolysis is low in energy efficiency, and, hence, it is a long way from being commercialized. In fact, the energy efficiency of the process is lower than those of other hydrogen production systems using solar light systems combining photovoltaic generation and water electrolysis, systems converting biomass into hydrogen, etc., by a factor of ten to several hundred. With this situation as a backdrop, there is a need to develop innovative photocatalysts that respond to long-wavelength visible light with sufficiently high quantum efficiency.

In addition to the above processes using semiconductor-type photocatalysts, the feasibility

Footnote 6:

Quantum efficiency refers to the ratio between the number of incident photons and the number of electrons involved in the reaction.

Footnote 7:

Sacrificial agents refer to additives (methanol, etc.) to be added in order to prevent generated hydrogen from being re-oxidized - a reverse reaction that produces water.

of photobiological hydrogen production — a system where hydrogen is produced by photosynthesis bacteria - is being examined,[19] with genetic engineering techniques being applied in developing photosynthesis bacteria. This hydrogen production system, however, requires a large amount of energy input — a factor that reduces the possibility of commercialization. The hydrogen production capacity of bacteria must be enhanced dramatically.

8.5 Conclusion

In this report, we have focused on the non-fossil-resources-based hydrogen production technology as the key to creating sustainable hydrogen energy systems, and discussed its significance from the viewpoint of future demand for hydrogen and its effects in conserving fossil resources and reducing greenhouse gas emissions. Moreover, we have divided the technology into the four categories of (1) water electrolysis, (2) thermochemical water splitting, (3) biomass conversion, and (4) water photolysis, analyzing trends in technological developments and issues to be addressed for each of these categories.

Fuel cells are energy-efficient in their nature. Take fuel cell vehicles for instance: they both significantly conserve fossil resources and reduce greenhouse gas emissions, even if they use hydrogen derived from fossil resources. As far as the results of our analysis are concerned, however, fuel cells do not outperform other competing technologies, such as hybrid vehicles, electric vehicles, combined cycle power generation, city gas cogeneration systems, etc.

When using hydrogen derived from non-fossil resources, meanwhile, fuel cells virtually eliminate fossil-resource consumption and greenhouse gas emissions. In this context, the non-fossil-resources-based hydrogen production technology is the key to creating sustainable hydrogen energy systems; it is particularly significant for Japan, whose self-sufficiency rates in energy remain at low levels.

Thus, Japan needs to pursue this technology on a long-term basis, placing emphasis on its research and development. Determining the potential of such ideal technology for producing hydrogen will provide fundamental information in developing not only long-term but also short-to-medium term energy policies and R&D strategies.

As we have discussed, all the methods excluding water electrolysis are still in their basic-study or demonstration stages; it is important that potential methods be explored widely and the feasibility of each method be assessed.

It is also important to grasp the role of hydrogen in the whole energy system, keeping track of advances in relevant technologies and changes in the global energy map. For instance, role sharing between electricity and hydrogen has yet to be determined.

Hydrogen is secondary energy along with electricity, functioning as a common currency among various energy systems. In this context, it involves all the aspects of energy such as its production, conversion, transportation and consumption. In designing energy systems including hydrogen energy, it is indispensable to bring up specialists well versed in energy-related technologies and policies. Moreover, exchanges of human resources in the energy field and cooperation among academia should be promoted.

It seems that hydrogen production using renewable energy holds great potential especially for developing countries where available land and renewable energy sources are abundant and many areas have no access to the electricity grid. It requires neither a large amount of initial investment nor advanced technology in plant maintenance.

From the viewpoint of technological development and international cooperation, therefore, it should be of benefit to Japan to actively develop technologies to be transferred to developing countries, while promoting local joint projects.

As is the case with technologies related to hydrogen production, each of which has been discussed in this article, there are also many challenges posed to the technologies related to the storage, transportation and utilization of hydrogen. For this reason, the hydrogen production technology of the future should be developed based on a broad perspective that includes advances in related technologies, improvements in related infrastructures and the usage of hydrogen energy.

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